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Response Surface Analysis of the SHOGUN Tube/Projectile Interface Model

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Prediction of the dynamic response of a projectile fired from a gun tube requires estimation of the interface loads between the gun tube and the projectile. Interface models have been developed to determine the loads induced by interaction between the gun tube and the projectile. The model incorporated in the SHOGUN gun dynamics code models the interface as a collection of linear and torsional springs. Precise values for the spring stiffness coefficients are not known. The effect of uncertainties in these coefficients upon the shot exit conditions of the projectile can be evaluated using experimental design methodology. In this report, the response surfaces for two projectile shot exit parameters are examined. This methodology is shown to provide several benefits over the typical method of parametric sensitivity studies. It is also shown how this method can reveal idiosyncracies in the interface model which may not be revealed using a typical sensitivity study.

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1. INTRODUCTION

The dynamic response of a projectile traveling in a gun tube is influenced by the material and geometric properties of the components of the gun system and the manner in which these components interact. The two primary components of the gun system which are typically considered are the gun tube and the projectile. The detail with which these components are modeled depends upon the intended application. Complex finite element (FE) models in which fine details are included are normally related to stress analysis predictions in which the survivability of the projectile components is of primary concern (Wilkerson 1990). Less detailed beam models which are capable of capturing the basic gross deformation of the projectile and tube during firing are routinely used to determine quantities such as the rigid body motion of the projectile during shot exit (Erline and Kregel 1990; Hopkins 1990).

Both modeling approaches require a means to determine the interaction forces which develop between the projectile and the gun tube during the interior ballistic cycle. The FE models use slideline techniques (Hallquist 1978). Changes in the projectile geometry are reflected by changes in the interface loads determined by the slideline algorithms. While accurate, these algorithms are often very complex and can result in substantial increases in computer execution time. The simpler beam models employ interface routines which attempt to model the tube/projectile interaction by a combination of linear and torsional springs which are compressed by the relative displacements between the gun and projectile components (Erline and Kregel 1990; Soifer and Becker 1987). These simpler models do not lead to substantial increases in computer execution times. However, valid values for the spring coefficients for different projectile geometries are difficult to determine.

Numerous iterations of an analysis may be required to determine the effect of changes in projectile design when the goal of the simulation is the determination of the effect of the interaction loads upon some characteristic of the dynamic response of the projectile. These iterations can be costly either because of increased computer time required by the FE models or additional runs required by the simpler beam models to explore the effects in uncertainties regarding appropriate spring coefficients. This iterative process is often referred to as a parametric or sensitivity study. The number of iterations required in the parametric study can be reduced while simultaneously increasing the quality of information obtained using experimental design methodology (E. I. Du Pont de Nemours & Co. 1988). The applicability of experimental design in computer simulation is illustrated in this paper by examining the dynamic response characteristics of a projectile to changes in the interface spring stiffness coefficients which determine the

loads between the projectile and gun tube in the interface model used in the SHOGUN gun dynamics code. The primary goal of the study is the determination of the response surfaces for two of the projectile shot exit rigid body motion parameters. Results for the predicted response surface of the angle of the crossing velocity vector, θ_v, and the angle of the angular velocity vector, $\theta_{\dot{\psi}}$, during shot exit are presented.

2. ANALYSIS

The interface between the gun and the projectile is modeled in SHOGUN as interacting beams coupled by linear and torsional springs (Figure 1). The linear spring describing the forward spring connection, X_3, can also have a clearance which is used to simulate impact. Altogether, there are seven parameters in the interface model. In this paper, only four of these parameters are varied. These four parameters are the two linear, X_1 and X_3, and two torsional, X_2 and X_4, spring coefficients. The ranges of these parameters are listed in Table 1. Shogun does not specify allowable values for these parameters, the ranges selected are intended to encompass values that may be considered reasonable. The order of magnitude of these values is based upon consideration of the actual structural stiffness of the components which the springs represent.

Table 1. Range of Factor Values

Factor	Value	
	Low	High
X_1(lb/in)	1.0×10^3	200.0×10^6
X_2(in lb/rad)	0.0	20.0×10^6
X_3(lb/in)	1.0×10^3	20.0×10^6
X_4(in lb/rad)	0.0	2.0×10^6

The three parameters not examined correspond to the clearance between the forward bell and the gun tube, and to two spring stiffness coefficients which couple angular displacement with radial loads. The clearance was not included in this study simply to reduce the complexity of the analysis. The effects of the spring stiffness coefficients which couple angular displacement with radial loads were not included

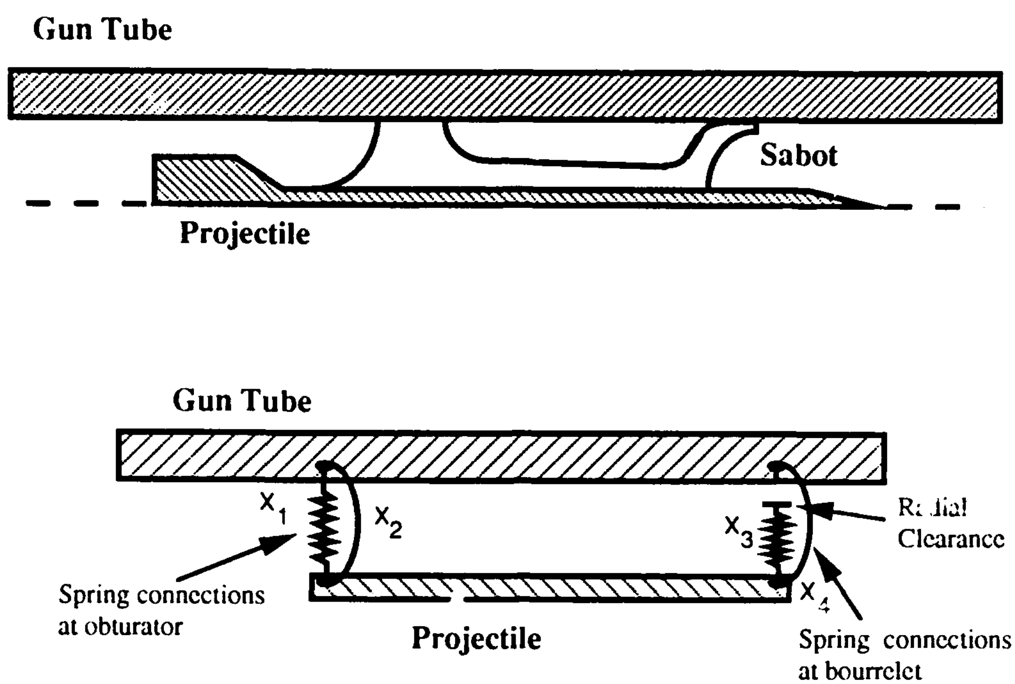

Figure 1. Gun tube/projectile interface model.

because the appropriateness and validity of these parameters is doubtful. For this study, the clearance was set to a fixed value of 0.004 in, based on projectile drawings, while the neglected stiffness coefficients were set to zero.

A face-centered cube (FCC) experimental design is used to determine which combination of values of the spring stiffness coefficients is used to generate the response surfaces. There are two primary reasons for using the FCC design. First, the data obtained allows precise estimation of the coefficients of a predictive equation. Second, the FCC design obtains information concerning the effects of the independent variables, called factors, at the extremes of high/low for each factor. A predictive equation is thus obtained which spans the entire factor space. These concepts are easily explained visually using an FCC design for three factors (Figure 2). It is seen that 15 data points are required—one at each corner, one at the center of each face, and one at the center of the cube. This design does not require replication of any individual data point. The corner points represent the extreme values of the factors. The midrange data point locations allow the determination of interaction and curvature effects. In this study, the FCC design for four factors requires a total of 25 data points to map the response surface. A deterministic process is one for which the system error is identically zero. This is the case for FE analysis since results

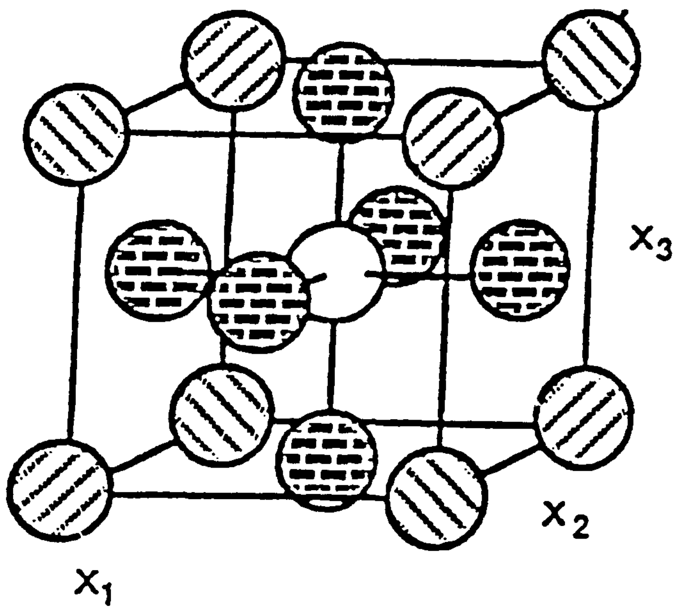

Figure 2. Three-factor face-centered cube.

for a given problem will not change from one computer run to the next. Thus, SHOGUN is a deterministic process.

Two response surfaces have been generated: the angle of the crossing velocity vector, θ_v, and the angle of the angular velocity vector, $\theta_{\dot{\psi}}$, during shot exit. These responses have been selected to illustrate the utility of the technique. The data gathered reveal that the torsional spring, X_4, does not affect the observed responses. Consequently, this factor is not considered in the subsequent numerical analysis of the data.

For each response, a quadratic polynomial of the form

$$
\begin{aligned}
Y = {} & b_o + b_1 Z_1 + b_2 Z_2 + b_3 Z_3 \\
& + b_{12} Z_1 Z_2 + b_{13} Z_1 Z_3 \\
& + b_{23} Z_2 Z_3 + b_{11} Z_1^2 \\
& + b_{22} Z_2 + b_{33} Z_3^2 ,
\end{aligned}
$$

where $Z_i = (X_i)^{1/2}$, is used to generate the response surface. This polynomial representation includes all linear, quadratic, and two-way interactions between the factors. A standard regression analysis is used to compute the coefficients of the polynomial. The units of these coefficients are simply those required to convert the response to radians. Thus, the units of b_o is radians, b_1 and b_3 are $(\mathrm{rad}^2\ \mathrm{lb/in})^{1/2}$, b_2 is $(\mathrm{rad/(in\text{-}lb)})^{1/2}$, etc. The coefficients of the polynomials for θ_v and $\theta_{\dot\psi}$ are presented in Table 2. Response surfaces for θ_v and $\theta_{\dot\psi}$, obtained for a constant value of X_3, are shown in Figures 3 and 4, respectively. Contour plots obtained from these surfaces are shown in Figures 5 and 6. Contour plots are projections of the response surface onto the Z_1Z_2 plane. The Z_1Z_2 plane corresponds to the square root of the range of values that can be used for the linear and torsional spring parameters of the obturator. Thus, this plane represents, indirectly through these stiffness parameters, the geometry of the obturator and the effect of the geometry on stiffness.

Table 2. Coefficient Values for Selected Responses

Y	b_0	b_1 $\times10^{-3}$	b_2 $\times10^{-3}$	b_3 $\times10^{-3}$	b_{12} $\times10^{-8}$	b_{13} $\times10^{-8}$	b_{23} $\times10^{-8}$	b_{11} $\times10^{-8}$	b_{22} $\times10^{-8}$	b_{33} $\times10^{-8}$	R^2_{adj}	RMS Error
θ_v	5.26	0.21	0.35	−1.40	−1.56	6.93	5.88	0.08	−5.10	10.21	0.87	0.47
$\theta_{\dot\psi}$	2.21	0.10	1.48	−0.89	−4.26	−1.41	6.27	0.15	−23.88	20.78	0.86	0.37

3. DISCUSSION

In the previous section, response surfaces were generated by fitting the data to a second-order polynomial. The selection of this polynomial represents a rudimentary model which is capable of capturing both curvature and interaction effects. No transformations were used on the responses θ_v and $\theta_{\dot\psi}$. However, the factors X_1, X_2, and X_3 were transformed using terms in powers of the square root of the factors. The square root transformation was selected based on the following observation. Examining Figure 1, it is reasonable to expect the interface model to behave in some sense like a simple spring-mass vibrating system. For this type of behavior, the response is proportional to the frequency of the system, which is, in turn, proportional to the square root of the stiffness (Meirovitch 1967).

The degree of success with which the response surfaces are represented can be quantified by examining the value of the adjusted R^2. Since there is no experimental error, R^2_{adj} represents the goodness

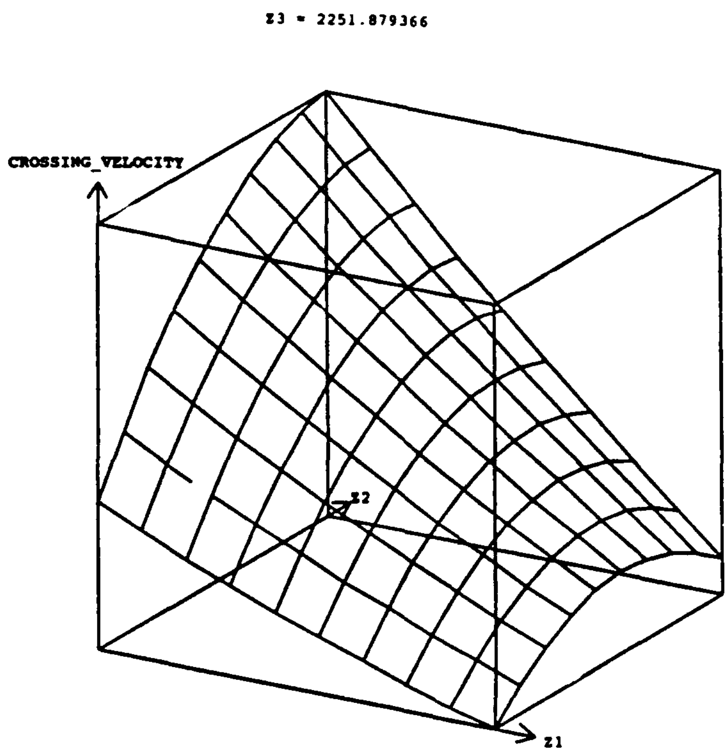

Figure 3. <u>Crossing velocity angular value</u>.

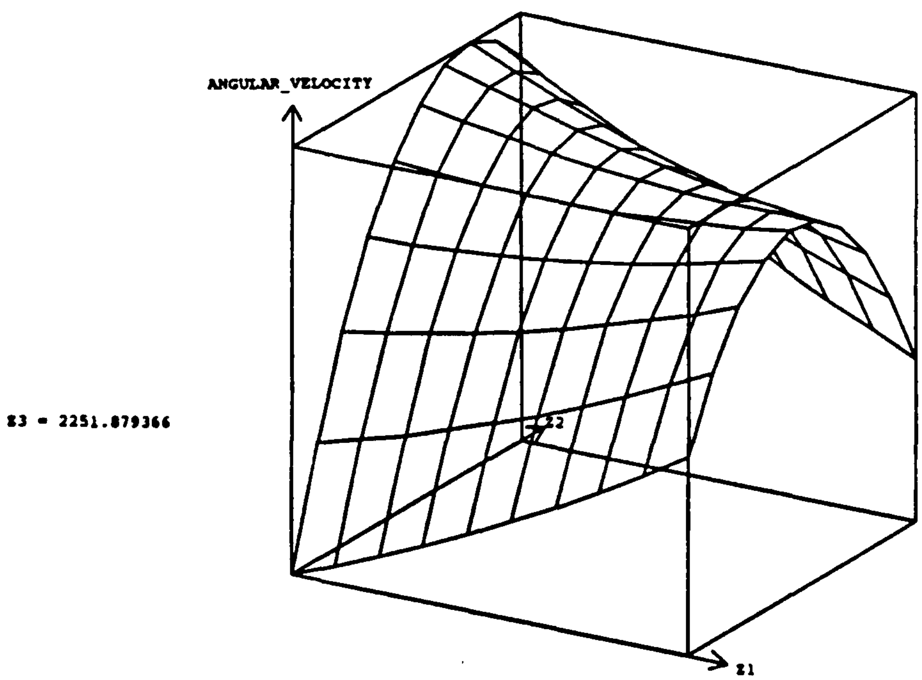

Figure 4. <u>Angular velocity angular value</u>.

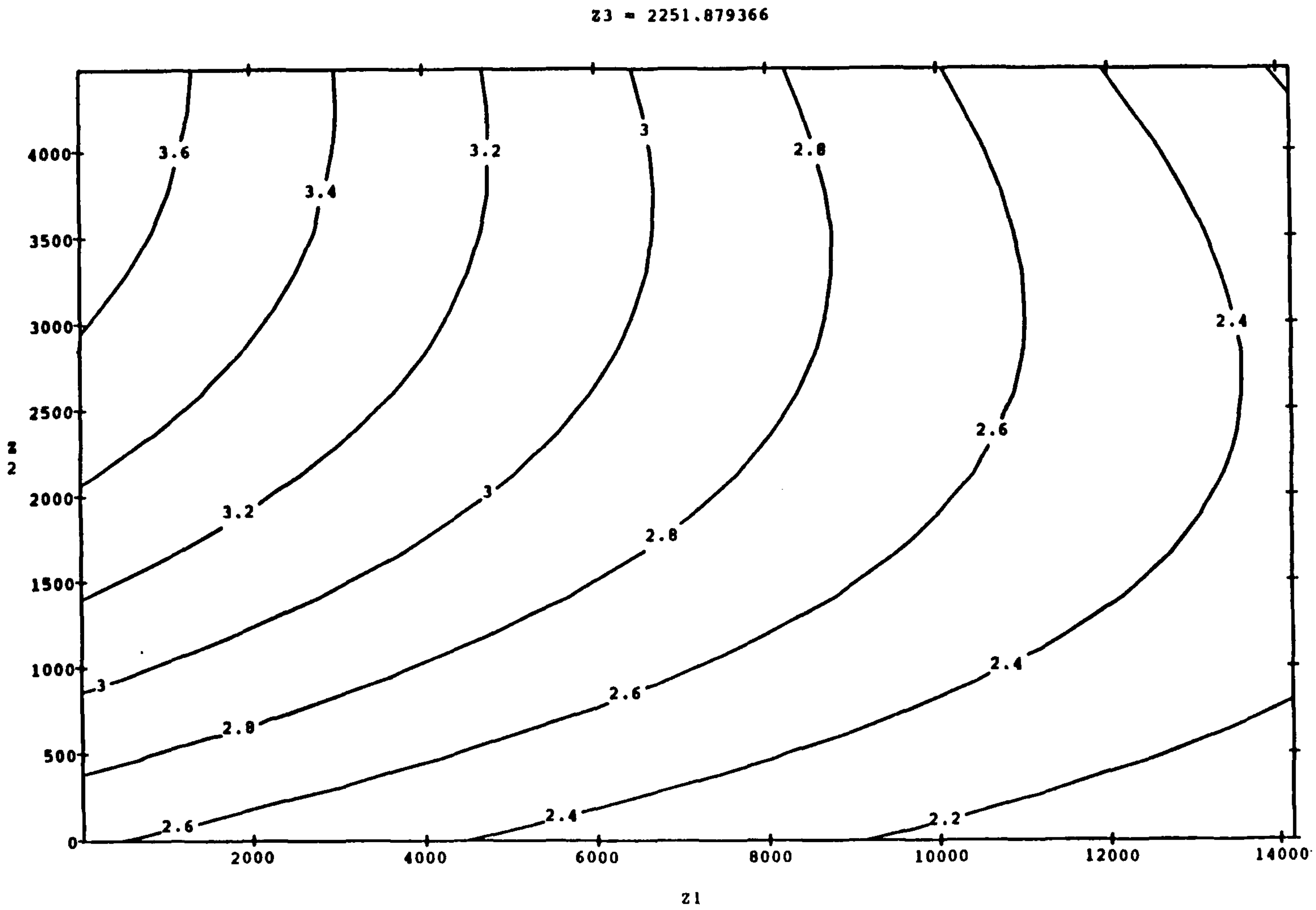

Figure 5. <u>Contour plot of crossing velocity angular value.</u>

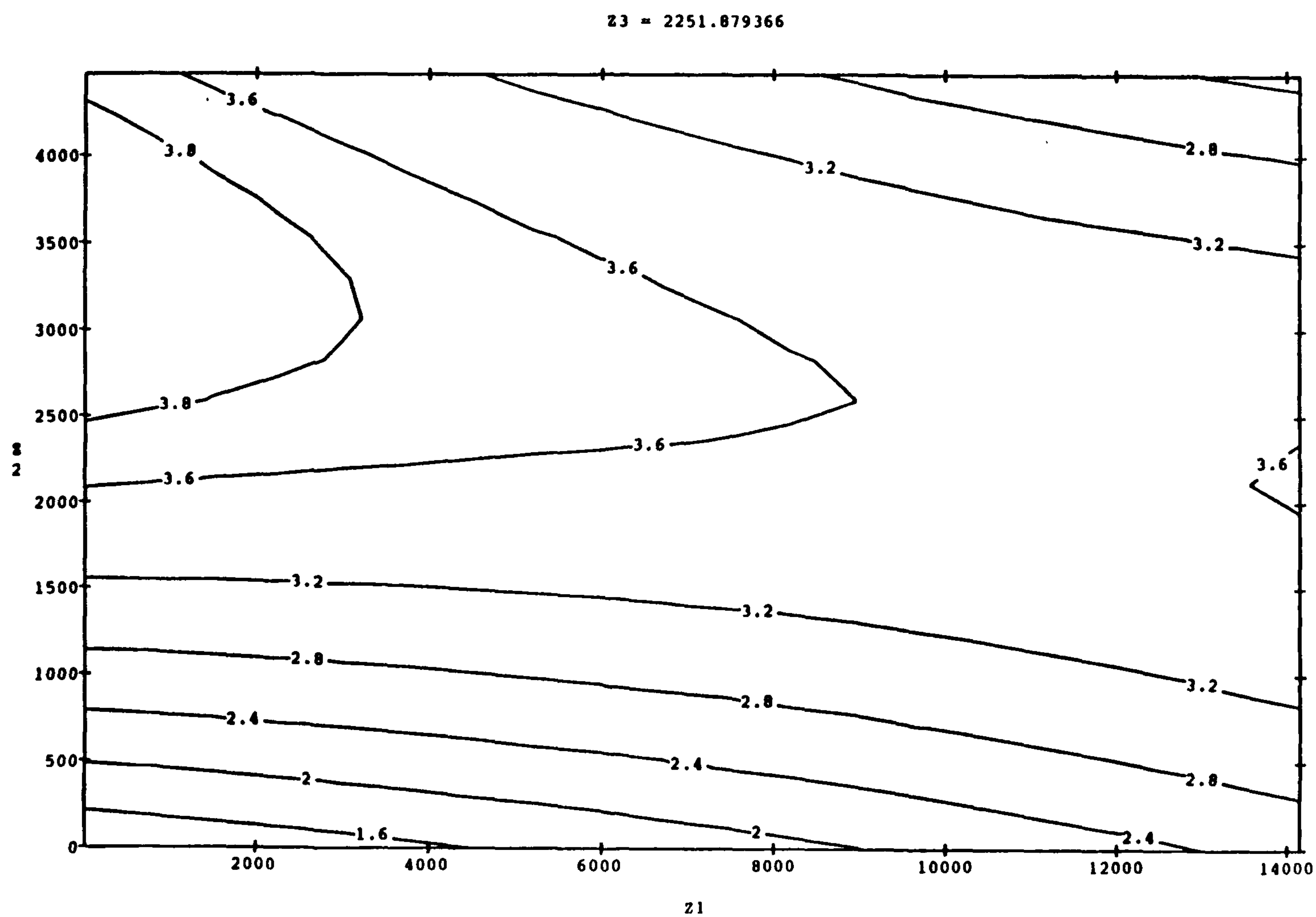

Figure 6. Contour plot of angular velocity angular value.

of fit of the model. R^2_{adj} values for both models are listed in Table 2. For θ_v, R^2_{adj} is 0.87; while for $\theta_{\dot{\psi}}$, R^2_{adj} is 0.86. This means that 87% or 86% of the total variation in the response of θ_v or $\theta_{\dot{\psi}}$, respectively, is explained by the model. The residual mean square (RMS) error is 0.47 and 0.37 for the two responses, respectively. Generally, the RMS error is a direct estimate of the combination of system error and model lack-of-fit. Since system error in this study is zero, the RMS error indicates directly the goodness-of-fit of the response surface to the exact surface over the entire range of the factors. Another means of checking the accuracy of the response surface models is by comparing the predicted values of θ_v and $\theta_{\dot{\psi}}$ with the actual results of SHOGUN which were used to generate the surfaces. This comparison is shown in Table 3. It is noted that there are several points which exceed the RMS error estimate by appreciable amounts. Although not perfect, the overall goodness-of-fit of the response surface models is adequate to capture the basic topology of the response surfaces.

The fact that factor X_4 does not affect the observed responses in any manner is disconcerting. There are four possible explanations for this behavior. First, it is possible that over the range selected, there is indeed absolutely no contribution to the response which can be attributed to X_4. This is highly improbable. Second, X_4 is affected by the value of the clearance parameter. The clearance parameter is one of the parameters held constant in this study. It is possible that the X_4 value selected allowed X_3 to affect the response while constraining any effect due to X_4. Third, there may be a coding error in the SHOGUN loading algorithm. Fourth, the SHOGUN interface model may not correctly model the effect of X_4. At this point, it is not known which of these explanations is correct.

The two response surfaces illustrate several important features. Consider the response surface for θ_v. The overall shape is basically a conic section. The minimum value of θ_v for a fixed value of X_3 occurs when X_1 is maximized and X_2 is minimized. This can be seen directly from Figure 3. The maximum response for θ_v is obtained when X_1 is minimized and X_2 is maximized. Generally, increasing X_1 while decreasing X_2, at a fixed value of X_3, results in a lower value of θ_v.

Next, consider the response surface for $\theta_{\dot{\psi}}$, which has a saddle point. The minimum value of $\theta_{\dot{\psi}}$ is obtained when X_1 and X_2 are both minimized. However, in this region, relatively small changes in either factor result in relatively large changes in the response $\theta_{\dot{\psi}}$ when compared to the saddle region of Figure 6. This saddle region is often referred to as a "robust" region. If sensitivity of $\theta_{\dot{\psi}}$ to variations in X_1 and X_2 is to be minimized, then values of X_1 and X_2 should be selected such that the response is in the saddle region. From Figure 6, the desired ranges are thus $64\times10^6 < X_1 < 200\times10^6$ and $4\times10^6 < X_2 < 10\times10^6$. In this region, the response is approximately 3.6 radians.

Table 3. Comparison of Actual and Predicted Response Values

Factors			θ_v (rad)		$\theta_{\dot{\psi}}$ (rad)	
X_1 (lb/in)	X_2 (in-lb/rad)	X_3 (lb/in)	Actual	Predicted	Actual	Predicted
$1(10^3)$	0	$1(10^3)$	5.5148	5.2044	2.2737	2.1873
$200(10^6)$	0	$1(10^3)$	2.1941	2.4140	3.7980	3.8907
$1(10^3)$	$20(10^6)$	$1(10^3)$	5.6086	5.7613	3.9130	4.0244
$200(10^6)$	$20(10^6)$	$1(10^3)$	2.4694	1.9853	3.1472	3.0371
$1(10^3)$	0	$20(10^6)$	.7462	1.0570	2.2697	2.3810
$200(10^6)$	0	$20(10^6)$	2.7105	2.6094	3.3102	3.2003
$1(10^6)$	$20(10^6)$	$20(10^6)$	3.0438	2.7805	5.5231	5.4628
$200(10^6)$	$20(10^6)$	$20(10^6)$	2.8527	3.3473	3.5512	3.5914
$1(10^3)$	$10(10^6)$	$10(10^6)$	2.8187	3.0481	4.5347	4.3801
$200(10^6)$	$10(10^6)$	$10(10^6)$	2.8689	2.6226	3.3285	3.5576
$100(10^6)$	0	$10(10^6)$	2.2591	2.0213	3.2197	2.1729
$100(10^6)$	$20(10^6)$	$10(10^6)$	2.4841	2.7044	2.9335	2.9867
$100(10^6)$	$10(10^6)$	$1(10^3)$	2.4578	3.3134	2.3167	4.2730
$100(10^6)$	$10(10^6)$	$20(10^6)$	3.9311	3.0589	4.6690	4.7222
$100(10^6)$	$10(10^6)$	$10(10^6)$	2.7004	2.7153	3.7685	3.7374

4. CONCLUSIONS

Using techniques of statistical design, response surfaces for two measures of projectile behavior have been generated. The generation of these surfaces requires 25 data points. These response surfaces are adequate to determine the relative influence of the stiffness coefficients used to model the tube/projectile interface in the SHOGUN gun dynamics code. The response $\theta_{\dot{\psi}}$ can be strongly affected by changes in either X_1 or X_2. However, because the response surface for $\theta_{\dot{\psi}}$ exhibits a saddle point, the sensitivity of $\theta_{\dot{\psi}}$ to change in X_1, or X_2 can be mitigated by keeping the values of these parameters within the range of values defined by the saddle region.

Since the goal of this report was to introduce the reader to the fundamentals of response surface analysis and experimental design as applied to computer simulation, the response X_3 was only analyzed at one level. Hence, no definitive conclusions can be drawn.

The factor X_4 did not have any effect upon the responses selected. Several possible reasons for this observation have been postulated, but at present the correct explanation is not known.

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